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REVIEW AND EVALUATION OF THERMAL SENSORS FOR USE IN TESTING FIREFIGHTERS PROTECTIVE CLOTHING

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REVIEW AND EVALUATION OF THERMAL SENSORS FOR USE IN TESTING FIREFIGHTERS PROTECTIVE CLOTHING

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Final Report

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Notice

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Final Report on

Review and Evaluation of Thermal Sensors For Use In Testing Firefighters Protective Clothing

Submitted to

National Institute of Standards and Technology

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Overview

The Center for Research on Textile Protection and Comfort (T-PACC) at North Carolina State University conducted a project which had, as its primary objective, the selection and evaluation of sensors that can be used to measure heat transferred through firefighter protective clothing materials, with the ultimate goal of applying this knowledge base to the development of rugged, and dependable laboratory benchtop and fire scene specific sensor technology. The purpose of this final report is to summarize the findings of this project and to recommend future directions in protection measuring heat flux sensor development.

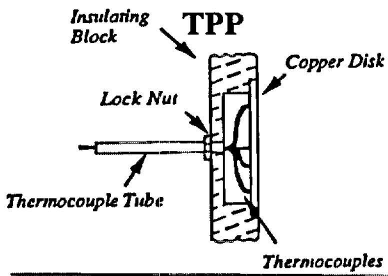
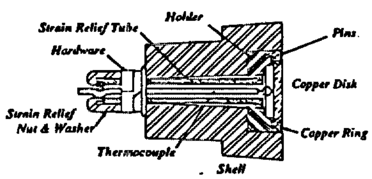
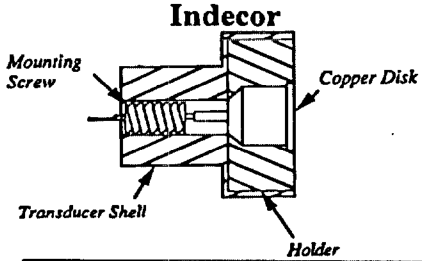
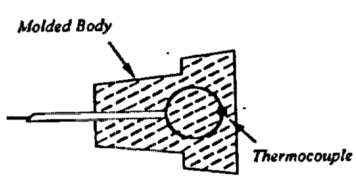
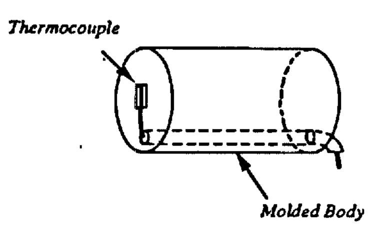
Summary of Progress

Non-cooled sensor technology was initially investigated for this application. A review of state-of-the-art surface heat flux measuring devices confirmed the existence of a variety of sensor options, including devices that utilize buried thermocouple transducers, slug or heat capacitance calorimeters, thin foil or Gordon transducers, wafer type thermocouple transducers and suspended disk thermocouple transducers [1, 2, 3, and 4]. Based on stated applications and instrumental needs, four different thermal sensors were selected for comparative testing and evaluation by this program (Table 1). A fifth sensor called "Pyrocal" , built at NCSU, was included in this project in order to address the disadvantages encountered in the available sensors.

The Pyrocal sensor is smaller and far less bulky than the TPP calorimeter having less heat loss and more rapid response times. Pyrocal has the additional advantage of possessing a small mass in comparison to the TPP calorimeter (1.3 grams vs. 17.9 grams). This is an important consideration, since the smaller mass of the Pyrocal sensor significantly reduced heat sink effects associated with the use of the TPP calorimeter. This contributed to improve the accuracy of the bench top TPP tests when used in sample mounting configurations that require intimate contact between the thermal sensor and the test fabric.

Although other existing non-cooled sensors that utilize surface mounted thermocouples (ThermoMan® and Alberta type) performed comparatively well in our thermal tests, they lacked the durability in use that can be expected from the Pyrocal device. Most significantly, the Pyrocal sensor overcomes a significant drawback associated with existing sensors. It does not require an inverse heat transfer calculation to estimate heat flux. This avoids errors associated with thermocouple location, and the mathematics of the heat transfer calculations. Direct heat flux measurements, using the Pyrocal sensor, circumvent these errors and provide a more accurate direct reading.

Table 1. Thermal Sensors

Sensor	Specifications*	Advantages/ Disadvantages
TPP 	Copper Slug Calorimeter $d_s = 4.0$ cm, $L = 0.16$ cm $d = 4.0$ cm, $b = 0.16$ cm $m = 17.89$ g Four J-type Thermocouples	• Adequate response time • Durable • Accurate measure of heat flux • Unknown heat leakage • Withstands long exposures • Small deviation
Pyrocal 	Copper Slug Calorimeter $d_s = 2.63$ cm, $L = 2.66$ cm $d = 1.27$ cm, $b = 0.15$ cm $m = 1.31$ g One T-type Thermocouple	• Adequate response time • Durable • Accurate measure of heat flux • Known heat leakage • Withstands long exposures • Small deviation
Indecor 	Copper Slug Calorimeter $d_s = 2.63$ cm, $L = 3.81$ cm $d = 1.31$ cm, $b = 0.16$ cm $m = 1.915$ g One T-type Thermocouple	• Slow response time • Durable • High variability • Significant deviation • Unknown heat leakage • Withstands long exposures • Screw acts as a heat sink
Thermoman® 	Thin-skin calorimeter Buried thermocouple in thermoset polymer $d_s = 2.6$ cm, $L = 2.7$ cm One T-type Thermocouple	• Fast response time • Limited durability • Small deviation • Errors due to inaccurate thermocouple bead location • Polymer cracks with repetitive exposures
Alberta 	Slug-type sensor Surface thermocouple on colorceran $d_s = 1.9$ cm, $L = 3.2$ cm One T-type Thermocouple	• Fast response time • Limited durability • Accurate measurement • Small deviation • Cannot withstand long exposure at high heat flux • Exposed thermocouple

*d_s = diameter of calorimeter
L = length of calorimeter
d, b, m = diameter, thickness and mass of the copper disk in slug-type calorimeters.

The Indecor sensor performed very poorly and was excluded from the study. Other sensor technologies have been found to have major limitations for our application. In-depth thermopile calorimeters are very flux range specific and commercial circular foil type calorimeters are limited to fluxes above 3.5 w/sq cm. Both of these types are limited to surface temperatures of about 400 F unless metals are used throughout. However, epoxies are often unavoidably used in the construction of many of these sensors. The in-depth thermopile and the circular foil calorimeters can be precision calibrated to specific temperature ranges, however, at high exposures sensitivity drops off rapidly. A complete description of the procedures used to evaluate the sensors and calculate heat flux and burn times was detailed in the 1997 Annual Report [6].

Both the calorimeter type and thermocouple type sensors, which have been investigated in this study, were limited to relatively short exposure duration, usually a few seconds at a time. These sensors are constructed of materials that retain heat during the exposure sequence. Subsequently, the sensor internal temperature rises to levels that would make the sensor unable to accurately measure the incident heat flux. To a certain extent, all of these sensors become impaired at long exposure durations. Therefore, dynamically cooled sensor technology was subsequently explored.

Existing technology was reviewed. This project identified and installed two state-of-the-art water cooled thermal sensors. The Thermogauge™, manufactured by Vatell Corporation [12], is a circular foil heat flux gauge that operates by measuring the temperature differential between the center and the circumference of a thin constantan foil disk. The constantan foil is bonded to a cylindrical copper heat sink. The voltage output from these materials is read as a means of calculating the absorbed heat flux. The Hy-Cal Hy-Therm® sensor is used to measure heat flux in many applications [13]. The Hy-Therm® sensor is also a circular foil heat flux gauge.

A prototype water cooled thermal flux sensor was developed at NCSU and critically compared to feasibly applicable "off-the-shelf" technologies, identified earlier in this study. Fluid cooled sensing devices were chosen because they permit reliable measurement of heat flux over longer exposure durations than possible with slug calorimeters. The NCSU prototype sensor was found to be capable of precisely measuring heat flux in prolonged exposure to radiant heat both at low (0.15 cal/cm^2 sec) and high (2.0 cal/cm^2 sec) flux levels . The sensor design concepts derive from the notions used in designing the time tested TPP, copper total heat flux slug calorimeters, i.e.;

- Rugged.
- Long lasting.
- Insensitive to hostile environments.
- Uses first principles.
- Easy to calibrate and maintain.
- Same sensor used for incident source flux and behind-the-fabric measurement.

The resultant prototype addresses all these issues. The water cooled copper disk design with continuous monitoring of incoming and outgoing water temperatures and of disk temperature, allows direct and continuous determination of heat flux at the sensor surface. Flux readings obtained are translatable to burn times using the original Stoll skin burn criteria [5] of incident heat flux versus exposure time.

During the final phases, the focus of the project has been on experiments to compare performance characteristics of the NCSU prototype to commercially available devices, including the Hy-Cal Hy-Therm® and the Vatell Thermogauge® , to gauge the precision, stability and sensitivity of the new sensor and to assess the performance of the prototype sensor when used in a TPP type setup behind a multilayered fabric system used in firefighting turnout ensembles.

This study provides foundation for the development of a promising thermal sensor for this application.

Background

In many industrial settings, workers face potential exposure to fires hazards. This is especially true for fire fighters who may be exposed to many different thermal environments including severe flashover conditions. Exposure may result in skin burns or loss of life. Investigations show that fire fighters can be exposed to intense heat flux levels as high as 4 w/cm^2 for relatively short periods of time [8]. Much work has gone into the characterization of the thermal environments experienced by firefighters [10]. Although protective clothing is available, quantitative evaluation of such clothing has typically been through small scale thermal protective performance tests (TPP) which measure heat transmission to the skin. With the use of thermal heat flux sensors, these tests give useful information about thermal protection [5].

An interest in sensor technology lies with the ability to predict burn damage levels that human skin would incur if a live subject had been exposed to similar conditions. Currently, a test procedure and facility exist on the campus of North Carolina State University at the College of Textiles for the purpose of assessing the extent and severity of human skin burn damage. The facility was designed to expose a clothed human mannequin to flash fire conditions. The potential skin burn damage can be evaluated using computer models when the local heat flux to the "skin" surface is known. The local heat flux is measured by 122 sensors mounted on the mannequin's surface. By varying the heat flux and exposure time, different accident scenarios can be simulated [9]. The information that these sensors provide is very useful in assessing a garment's overall effectiveness at protecting a person from serious burns or death during a flash fire exposure. There is, however, a broad range of thermal injury that may be sustained by firefighters [11]. For this reason, it is important that accurate measurements of heat flux be obtained at a variety of heat flux levels.

Physiological burn damage rate models are based on knowledge of the intensity and duration of incident heat flux on the skin surface. Precise detection of surface heat flux incident level is, therefore, a key factor in calculating the burn damage predictions. The value of heat flux is dependent on the nature of the heat source but also upon both the thermal conductivity and surface temperature of the sensor, therefore, selection of a transducer is important. A sensor of inappropriate design may provide misleading results [9]. To evaluate the capabilities and limitations of different sensor technologies, an analysis of engineering design specifications must be made.

In order for the heat flux measuring devices to be analyzed, a list of performance requirements was prepared. The list was subdivided into two categories—application requirements and instrument requirements. To offer a better understanding , a description of the requirements is outlined below:

Performance Requirements

Application Requirements

The potential applications for the thermal sensor include use in bench-scale tests of the thermal protective performance (TPP) test of firefighter clothing materials, use in instrumented manikin (PyroMan type) tests, and use as an instrument to characterize full scale or field exposures to structural firefighting environments. In light of potential applications a reasonable set of requirements follows:

- The thermal sensor should be small and lightweight. It should be rugged and sufficiently durable to withstand repeated exposures in laboratory tests of firefighter clothing materials or for use in full scale field evaluations of firefighter thermal exposures.

- For applications in testing firefighter clothing materials and thermal exposures, the sensor must be capable of accurately and reliably measuring both convective and radiant heat flux in an operating range of 0 to 2.5 $cal/cm^2 \cdot sec$ (10.5 w/cm^2).

- The thermal sensor must produce an output that can be unequivocally translated by an acceptable skin burn damage model. The translation from instrument response to predict skin burn injury should not require baseline calibration and an initial rate of temperature rise measurement.

- The optimal sensor should feature a design concept that can be easily and reliably manufactured in quantity with acceptable production economy.

Instrument Requirements

- The thermal sensor must provide a rapid response for proper data acquisition. Rapid response is an important consideration contributing to enhance the value of the heat flux measurement for use in predicting the level of skin burn damage.

- The sensitivity of the thermal sensor must be such that it can detect heat flux in the lowest operating range with only slight variation due to heat leakage or thermal storage within the sensor. The sensor must output a strong and clean signal in such a manner that is immune from noise produced by extraneous electromagnetic interference.

- The sensor design should minimize storage of thermal energy that can occur in repetitive heat exposures. Heat storage is undesirable since it contributes to inaccuracy in the thermal measurement, especially at high heat flux levels.

- The sensor should have minimum impact on the thermal history of the overlaying materials through heat sink or temperature gradient effects.

Application Conditions

In order to select appropriate test methods and specifications, the conditions under which protective clothing will be used must be considered. However, it is quite difficult to completely to define the firefighter environment. This is because of the many environmental, physical, physiological and psychological factors that effect a firefighter's interaction with the fire scene. Nonetheless, data has been collected and information is available to provide a range of common thermal environment conditions that are classified into three general categories. These classifications are identified as Routine, Hazardous and Critical, and are described in detail below.

- *Routine Conditions*: These conditions are applicable to firefighters who are operating hoses or otherwise fighting fires from a distance, where no special clothing is necessary. According to Foster et al. [7], the limits proposed are 25 minutes at 100 °C and a thermal radiation limit of 0.024 $cal/cm^2 \cdot sec$ (0.1 w/cm^2). According to Abbott et al. [8], routine conditions are those experienced in front of a small open fireplace, and present no real hazard to the firefighter. The firefighter can remain close to the fire safely without any protective clothing for a minute or two and extinguish it. Abbott associates conditional limits of 20-70 °C with thermal radiation of < 0.04 $cal/cm^2 \cdot sec$ (0.17 w/cm^2).

- *Hazardous Condition*: These conditions (described as "Ordinary" by Abbott et al.) are typical of those that would be encountered outside a burning room or small burning building. As reported by Hoschke [9], the lower bounds of this region are similar to firefighters ventilating a fire without water support, while the upper limits are applicable to those who are first into a burning building. Nonetheless, a "turnout" uniform is necessary to provide burn protection and to minimize thermal stress the firefighter may encounter. The range set by Foster et al. [7] has been taken to be at least 1 minute at 160 °C and a thermal radiation of 0.096 $cal/cm^2 \cdot sec$ (0.4 w/cm^2) and can be tolerated up to 10 minutes. Abbott et al. [8] describe this condition as lasting 10-20 minutes with air temperatures of 70 °C-300°C with thermal radiation of 0.04 $cal/cm^2 \cdot sec$ to 0.30 $cal/cm^2 \cdot sec$ (0.4 to 1.26 w/cm^2). Recent work has shown that some simple wastebasket fires may output up to 4 w/cm^2.

- *Critical Condition*: These conditions (described as "Emergency" by Abbott et al.) are not normally encountered by civilian firefighters. These conditions exist around a crashed aircraft when fiercely burning fuel exists. They may also be encountered during "flashover" of a large building fire. A proximity suit as well as special breathing apparatus must be employed when working with fires in this condition [9]. These conditions have been taken to be above the range of "Hazardous" conditions and ranging to beyond 235 °C and 0.23

cal/cm^{2}·sec (1 w/cm^{2}) by Foster et al. [7]. Severe thermal problems and life threatening injuries are associated with these conditions. Abbott et al. [8] describe these conditions as having temperatures of 300 °C to 1200 °C and 0.30 cal/cm^{2}·sec to 5.0 cal/cm^{2}·sec (1.26 to 20.9 w/cm^{2}).

Thermal Measurements in Prolonged Thermal Exposure

Application conditions, therefore, clearly indicate a need to evaluate the protective performance of firefighter clothing materials using conditions that simulate thermal exposures occurring near, or outside a flash fire environment. These firefighting conditions typically involve exposures to radiant thermal energy for periods that may last for several minutes. These conditions can exceed the useful range of calorimeter or slug type sensors, which are limited to relatively short exposure durations. The use of thermocouples presents a separate set of technical challenges including the ambiguities involved in heat flux calculation and skin burn injury estimation from thermocouple readings.

This research has made a significant effort to develop a prototype dynamically cooled thermal flux sensor that can be used to measure the thermal protective performance of firefighters clothing in prolonged exposures to heat. The objective of this effort was to demonstrate the conceptual feasibility and value of the prototype as a useful instrumental approach for this important application.

The design of the NCSU prototype sensor, and studies to define performance characteristics are described in subsequent sections of this report.

The NCSU Water-Cooled Prototype Sensor

After an exhaustive search of available "off-the-shelf" solutions we concluded that limited range, durability and especially concern over the proprietary nature of existing commercial sensor designs and calibrations, ruled out use of any of these technologies [15] . An "open system" sensor which can be user calibrated and even user modified to meet specific end-use scenarioes is what is required for our complex application. Therefore, emphasis was placed on the new small, lightweight sensor developed at T-PACC.

The system consists of a water cooled sensor, heat sensing thermocouples, cooling auxiliaries and data collection equipment (Figure 1). The sensor assesses incident heat flux by measuring the temperature rise in the copper slug calorimeter and the temperature of water after flowing through the system. The temperature rise in the coolant is calibrated in exposures to known levels of incident heat.

A differential thermal balance equation was used as:

$$\frac{dQ}{dt} = \frac{dm}{dt} Cp\Delta T$$

Where Q is the incident heat flux
ΔT is differential temperature and
m and Cp are the mass and specific capacity of the water flowing through the sensor.

This principal equation was used to estimate the magnitude of the water flow rate, dm/dt, required by the sensor. Details of these calculations are given in Appendix A to this report.

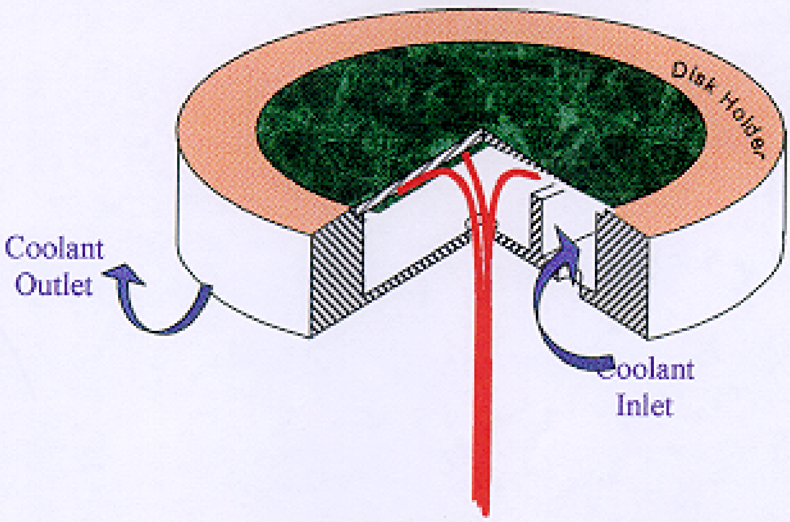


Figure 1. NCSU Water Cooled Sensor

Sensor Performance Studies

Laboratory experiments were performed to demonstrate the heat flux calculation protocol employed by the prototype sensor, and to determine its sensitivity to coolant flow rate and temperature. These tests were conducted primarily to validate the basic measurement principal utilized by the sensor and to provide baseline information that will facilitate the design and development of subsequent sensors having enhanced performance characteristics.

The experimental setup used to assess sensor performance is shown in Figure 2.

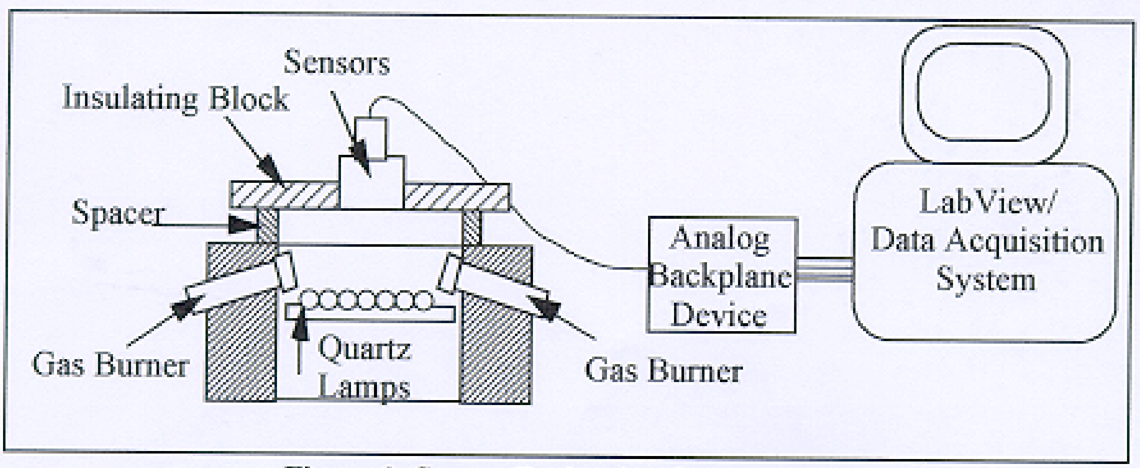


Figure 2. Sensor Evaluation Setup

The sensor output was fed to a 16-channel analog backplane device (National Instruments). The backplane device contained modules, which in addition to capturing nonlinear voltage readings from each sensor, isolated and linearized each signal. Output voltages were fed, from the analog backplane device, to an MIO board (AT-MIO-16F-5 DAQ) to generate time signatures for these signals. LabView software was used to translate voltage signals into temperature readings.

The sensors were exposed to the following conditions to evaluate characteristics and response:

Condition 1: 100% radiant heat source @ 0.15 cal/cm^2·sec bare exposure for 300 seconds
Heat source: bank of nine quartz tubes.

Condition 2: 100% radiant heat source @ 0.23 cal/cm^2·sec bare exposure for 300 seconds
Heat source: bank of nine quartz tubes.

Condition 3: 100% radiant heat source @ 0.35 cal/cm^2·sec bare exposure for 300 seconds
Heat source: bank of nine quartz tubes.

Condition 4: 100% radiant heat source @ 0.50 cal/cm^2·sec bare exposure for 300 seconds
Heat source: bank of nine quartz tubes.

Condition 5: 50/ 50 convective/ radiant heat source @ 1.25 cal/cm^2·sec bare exposure for 300 seconds
Heat source: TPP test configuration - flames and quartz tubes

Condition 6: 50/ 50 convective/ radiant heat source @ 2.00 cal/cm^2·sec bare exposure for 300 seconds
Heat source: TPP test configuration - flames and quartz tubes

The TPP calorimeter was used to set the nominal heat flux for each exposure condition. Replicate measurements were made at each exposure condition to determine the variability of consecutive thermal readings.

Initially, we conducted experiments designed to provide primary assessment of the sensor response to a 8.4 w/cm^2 (2 cal/cm^2·sec) thermal exposure. A 2 cal/cm^2·sec exposure was generated in a TPP test set up that utilized gas burners and radiant panel as the heat source. This exposure was maintained for a period of 3 minutes. The copper calorimeter sensor was cooled, throughout the exposure, by circulating water at a flow rate of 0.8 g/sec.

Figure 3 shows the manner in which the sensor temperature increased during the heat exposure. This behavior is indicative of conventional transient heat transfer response, through the first two minutes of the exposure. Beyond two minutes, fluctuations are symptomatic of air bubbles, trapped with the water within the sensor, and their effects on dynamics of the heat transfer.

Experiments continued to evaluate the response of the new sensor using higher water flow rates to minimize measurement instabilities related to the formation of air bubbles with the water coolant.

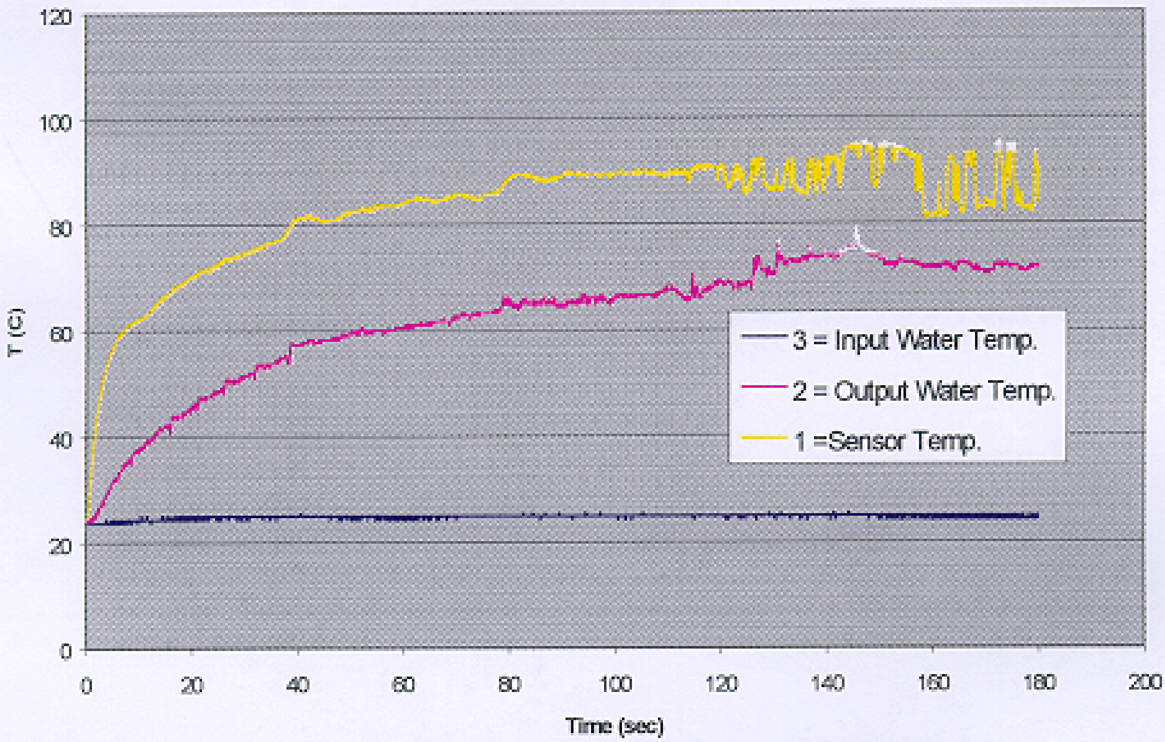


Figure 3. Temperature Response of NCSU Water Cooled Thermal Sensor Exposed to 8.4 w/sq cm Heat Flux for 3 Minutes.

Thereafter, the emphasis of experiments evolved toward the goal of qualifying the response of the sensor exposed to different levels of thermal energy. We also sought to define the relationship between the flow rate of the water coolant and sensor exposure to incident heat. For these tests the sensor was exposed to thermal energies ranging from 0.63 to 8.4 w/cm^2 (0.15 to 2.0 cal/cm^2·sec) for a period of 5 minutes. Throughout these exposures the sensor was cooled with water flowing at rates ranging from 0.94 to 2.33 g/sec. Figure 4 provides an example of the response of the sensor exposed to 0.63 w/cm^2 (0.15 cal/cm^2·sec) radiant heat with a water flow rate of 0.94 g/sec. The output shows the measured sensor temperature, and the entrance and exit temperatures of the circulating water. Figure 5 shows the difference between the rise in temperature of the sensor and the rise in coolant temperature (Δt) plotted as a function of exposure time. Figure 6 shows the experimentally determined relationship between Δt and incident heat flux for thermal exposure intensities ranging from 0.63 to 8.4 w/cm^2 (0.15 to 2.0 cal/cm^2·sec).

These experiments provided insights for utilization of the prototype sensor. They indicate that the sensor response stabilizes within the first 15 seconds of a 5 minute exposure to heat. They show that the sensor response is linearly related to the heat flux level of the exposure (Figure 6). This is a significant finding since it verifies that heat flux can be calibrated and reliably predicted from the instrument output. These experiments also reveal that, above a minimum rate (0.94 g/sec), sensor temperature rise is not dependent on the flow rate of the water coolant (Figure 7).

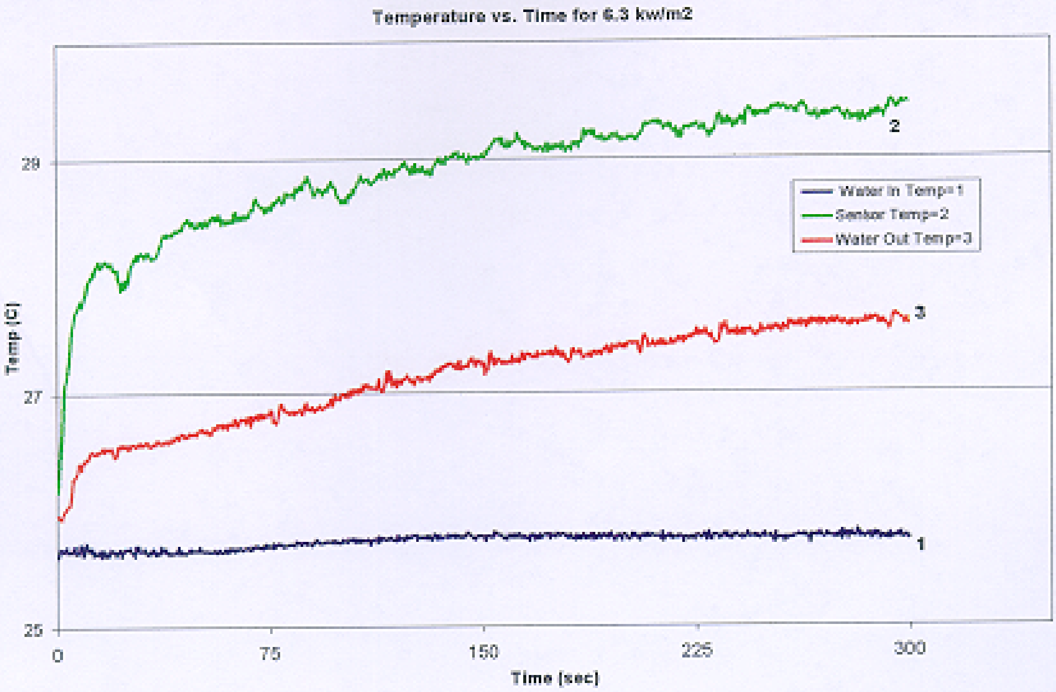


Figure 4. Sensor Temperature, Entrance and Exit Coolant Temperature vs. Time for a 0.63 w/ cm^2 for a 5 Minute Exposure (0.94 g/sec water flow).

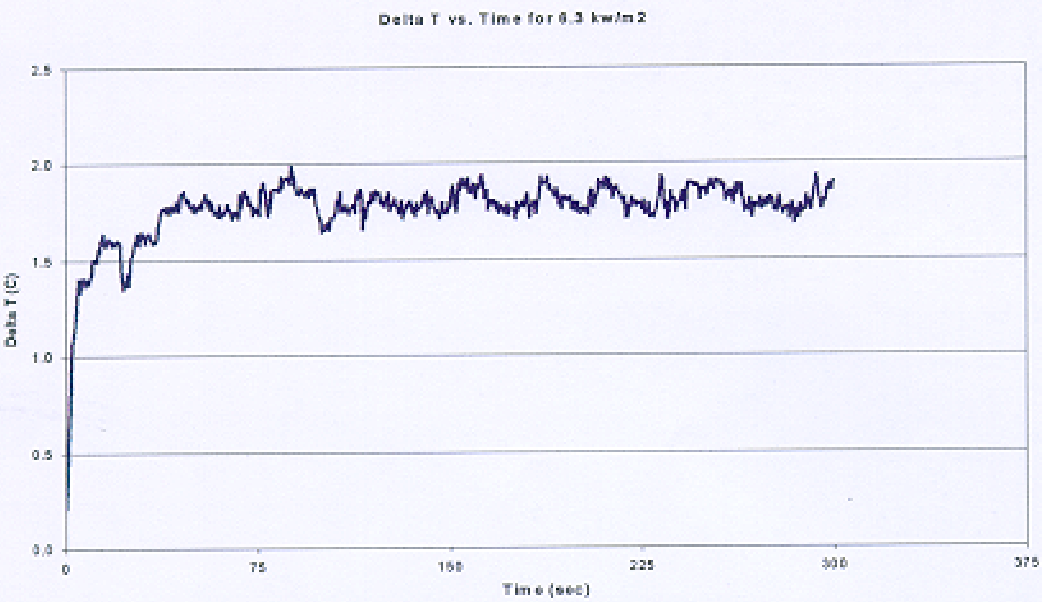


Figure 5. ΔT as a Function of Exposure Time at 0.63 w/ cm^2 (0.94 g/sec flow rate).

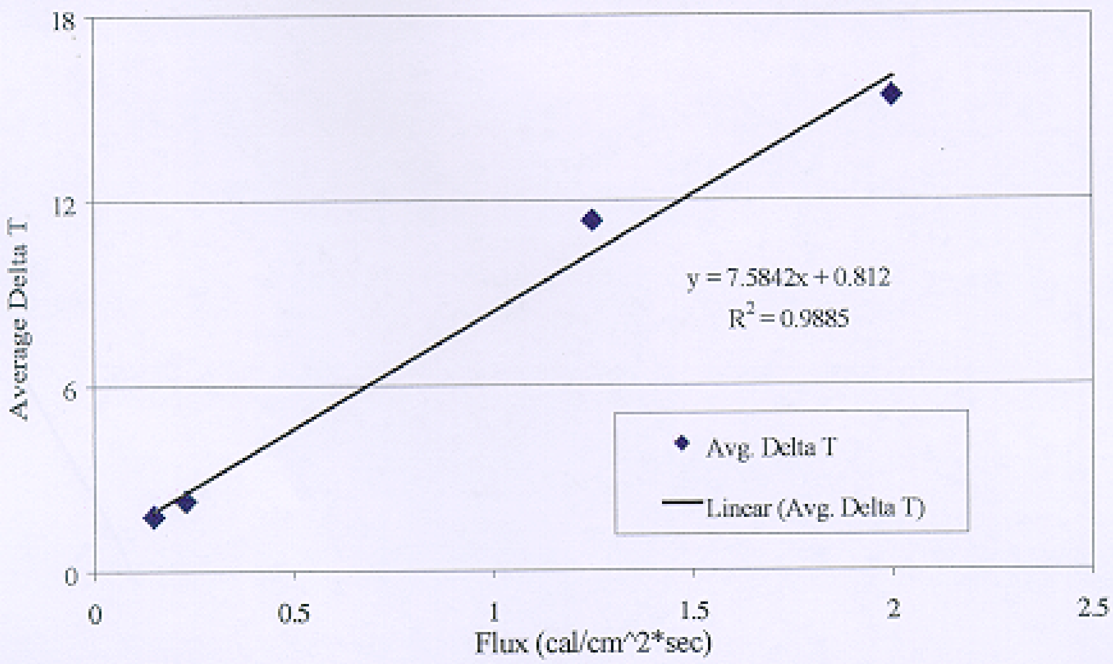


Figure 6. ΔT as a Function of Exposure Heat Flux (0.94 g/sec flow rate).

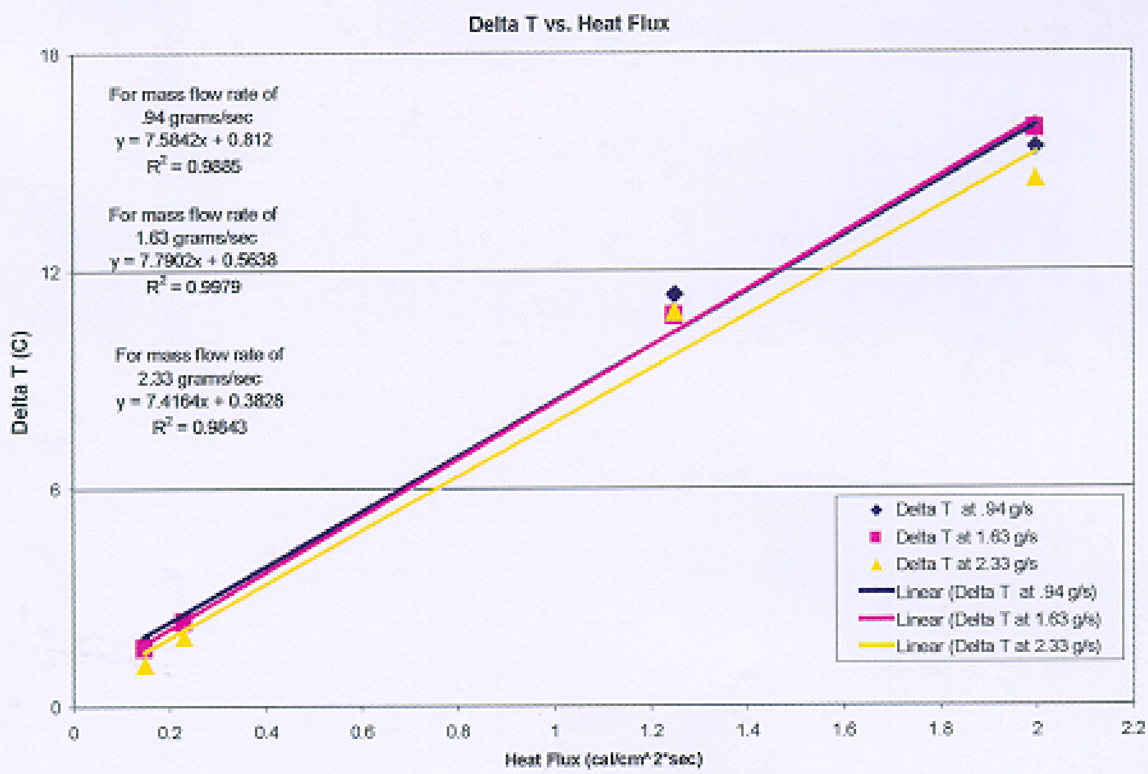


Figure 7. Average Difference in Temperature Between Copper Slug Sensor and the Temperature of the Exiting Coolant vs. Incident Heat Flux for Exposures Ranging From 0.15 to 2.0 cal/cm^{2}sec (0.63 to 8.4 w/cm^2) for Three Different Water Flow Rates.

Additional experiments were performed to gauge the stability and to compare the performance characteristics and sensitivity of the NCSU prototype sensor to commercially available devices, including the Hy-Cal Hy-Therm® and the Vatell Thermogauge™ sensors.

Experiments were performed that used 5-minute exposures to 0.6, 1.0 and 2.1 watts/cm^2 (0.15, 0.23 and 0.5 cal/ cm^2·sec) levels of radiant heat. The thermal exposure was set using a TPP type copper calorimeter as a reference.

Figure 8 shows the response of the different thermal sensors to the heat exposure. These experiments reveal the following performance traits:

- The Hy-Therm® device responds rapidly to heat and produces a stable output, throughout the duration of the thermal exposure. The Hy-Therm® indicates higher than the heat flux level set using the TPP calorimeter, at each of the three heat exposures tested.

- The Thermogauge™ sensor most accurately reflects the exposure setting at the lowest exposure levels (0.6 and 1.0 watts/ cm^2). It underestimates at the 2.1 watts/ cm^2 exposure level. It is observed to respond rapidly to heat, producing a stable signal throughout the thermal exposure.

- The accuracy with which the NCSU prototype indicates the set heat flux depended upon the exposure intensity: It underestimates the set heat flux at the lowest exposure level (0.6 watts/ cm^2), and indicates with more accuracy at the 1.0 and 2.1 watts/ cm^2 settings. The flux indicated by the prototype device is similar to that measured by the Thermogauge™ sensor at the 1.0 and 2.1 watts/ cm^2 levels.

The response of the NCSU water-cooled prototype sensor to heat is observed to be slower than for the Hy-Cal® and Thermogauge™ devices. The slower response can be attributed to the relatively higher mass of the copper disc used in the prototype sensor. This is a useful observation since it will assist the design of future prototypes, which can be fabricated to reduce thermal mass.

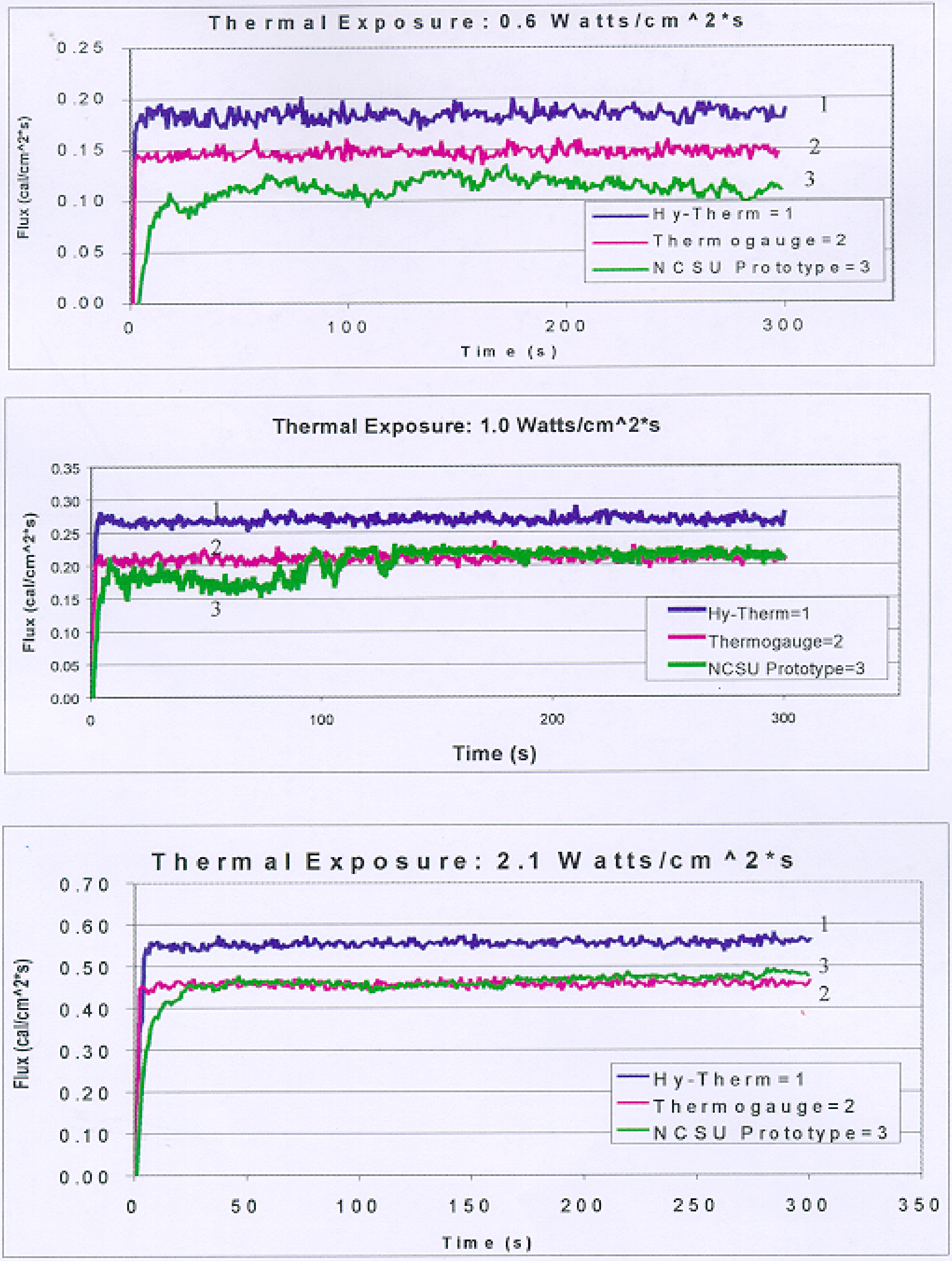


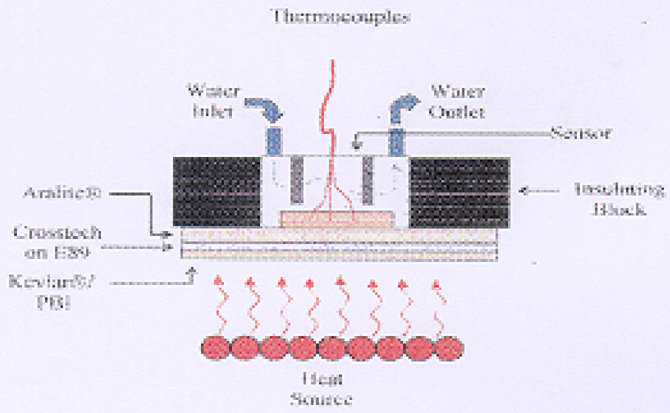
Figure 8. Characteristic Response of Thermal Sensing Devices to Three Different Levels of Exposure to Radiant Heat. (Indicated output is average of replicate tests.)

Testing Application of the NCSU Prototype Sensor

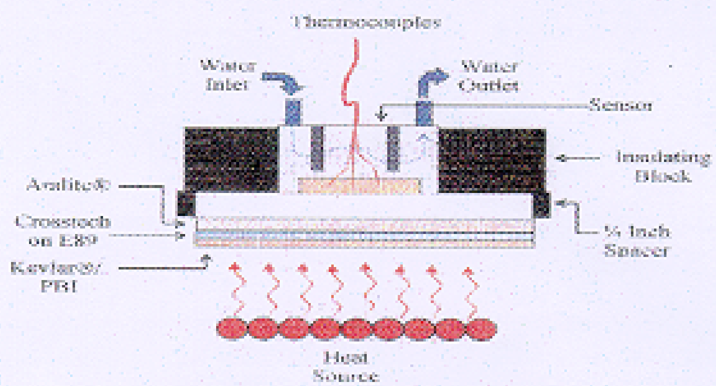
Studies were performed to provide information that will facilitate ultimate application of the NCSU water-cooled sensor. In these tests, the prototype device was used to measure heat transfer through a turnout assembly consisting of a Kevlar®/ PBI outer shell, Crosstech® on E89 moisture barrier and Aralite® thermal liner. The turnout composite was exposed for 5 minutes in a TPP type test configuration to a radiant heat source (bank of nine quartz tubes) set at 1.0 watt/cm^2 (0.23 cal/ cm^{2}sec). The sensor assembly consisted of the prototype water-cooled sensor mounted in a 6" x 6" insulating block (Figure 9). Tests included open back and closed back configurations:

Configuration 1: Prototype sensor assembly is in direct contact with the thermal liner side of the test composite.

Configuration 2: A spacer plate is used to create a 0.25 inch space between the prototype sensor assembly and thermal liner.



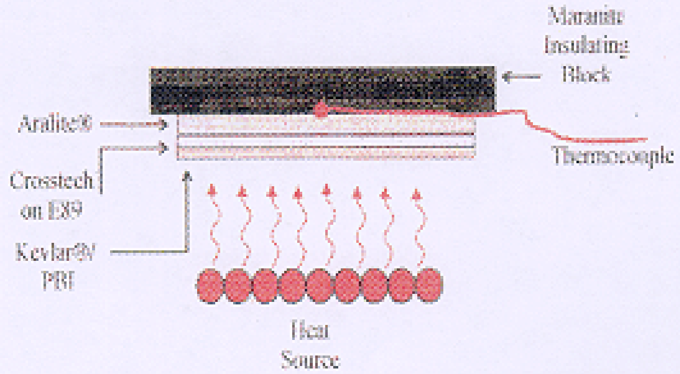
a. Contact Test Configuration



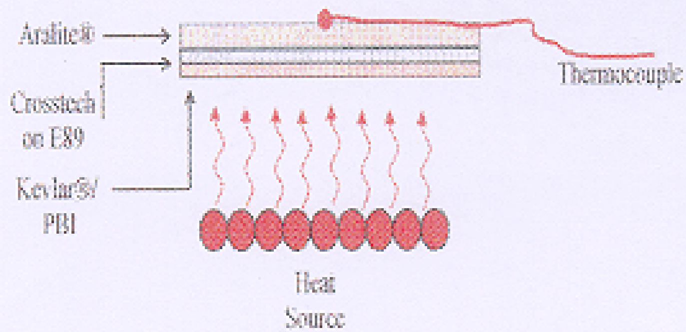
b. Spaced Test Configuration

Figure 9. Test Configurations Using NCSU Prototype Sensor to Measure Heat Transfer Through Turnout Composite.

For comparison, a parallel series of experiments were performed in which the same firefighter turnout composite was exposed, in a similar test set-up, except that a thermocouple was used in place of the water-cooled sensor to detect heat transfer through the test composite. In these experiments, a "T" type thermocouple was sewn to the back of the thermal liner. Tests were performed with both an open back system (the thermal liner was open to the environment) and a closed back system. The closed back system was configured by placing a 6" x 6" insulating block directly on top of the thermal liner. The experimental arrangements are illustrated in Figure 10.



a. Covered Back Test Configuration



b. Open Back Test Configuration

Figure 10. Test Configuration Using Thermocouple to Measure Heat Transfer Through Turnout Composite.

Figures 11 and 12 show the data produced by the above described experiments.

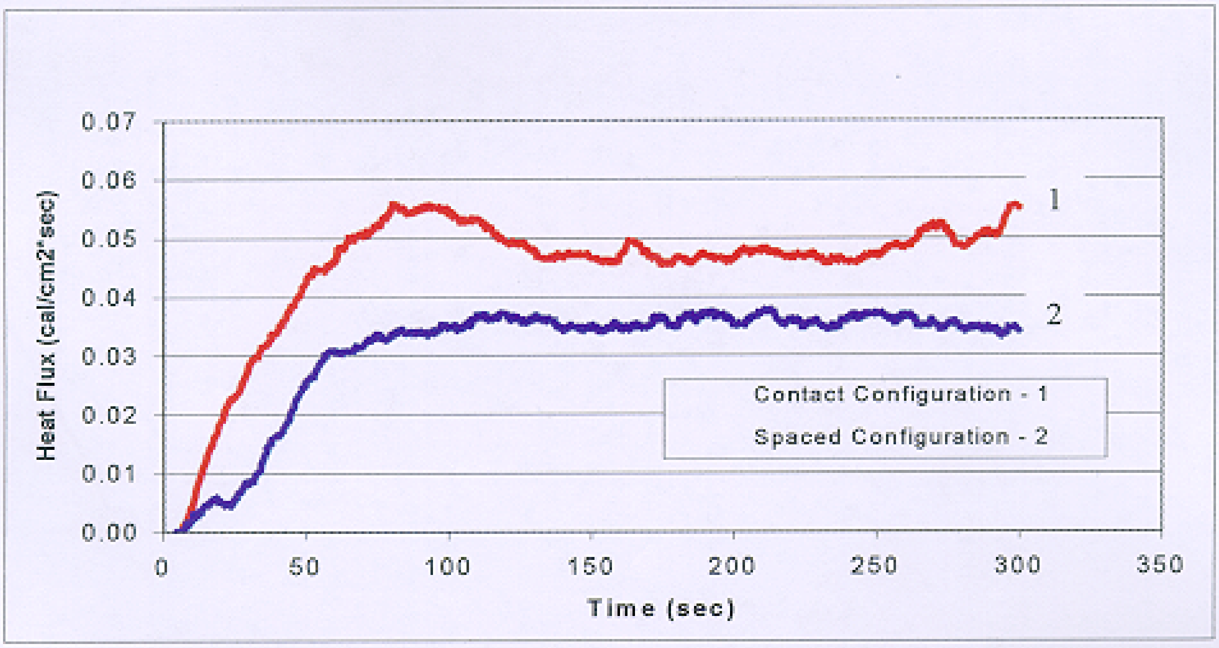


Figure 11. Effect of Testing configuration on Heat Flux Measured Through Turnout Composite by NCSU Water-Cooled Sensor. (1.0 watts/cm^2 radiant exposure).

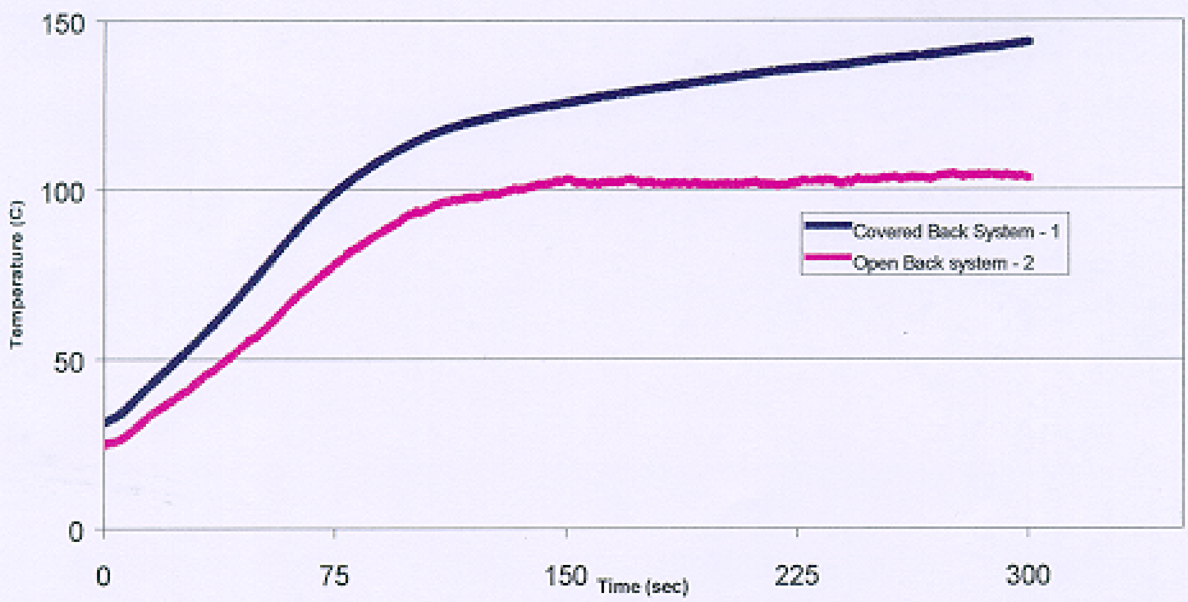


Figure 12. Effect of Testing Configuration on Temperature Measured by Thermocouples Attached to the Thermal Liner of the Turnout Composite (1.0 watts/cm^2 radiant exposure).

These results indicate the effects of different sample mounting configurations on the heat transfer, as characterized both by the water-cooled thermal sensor and by thermocouple measurements. For the water-cooled sensor, the contact configuration produces the higher heat flux reading (Figure 11). This confirms the expectation that the contact testing configuration measures the conductive heat transfer through the turnout composite. At the same time, the use of an insulating block behind the thermocouple (covered back system) allows a higher temperature reading in comparison to an open back system (Figure 12). These insights should be useful in comparing and interpreting thermal measurements made using these devices.

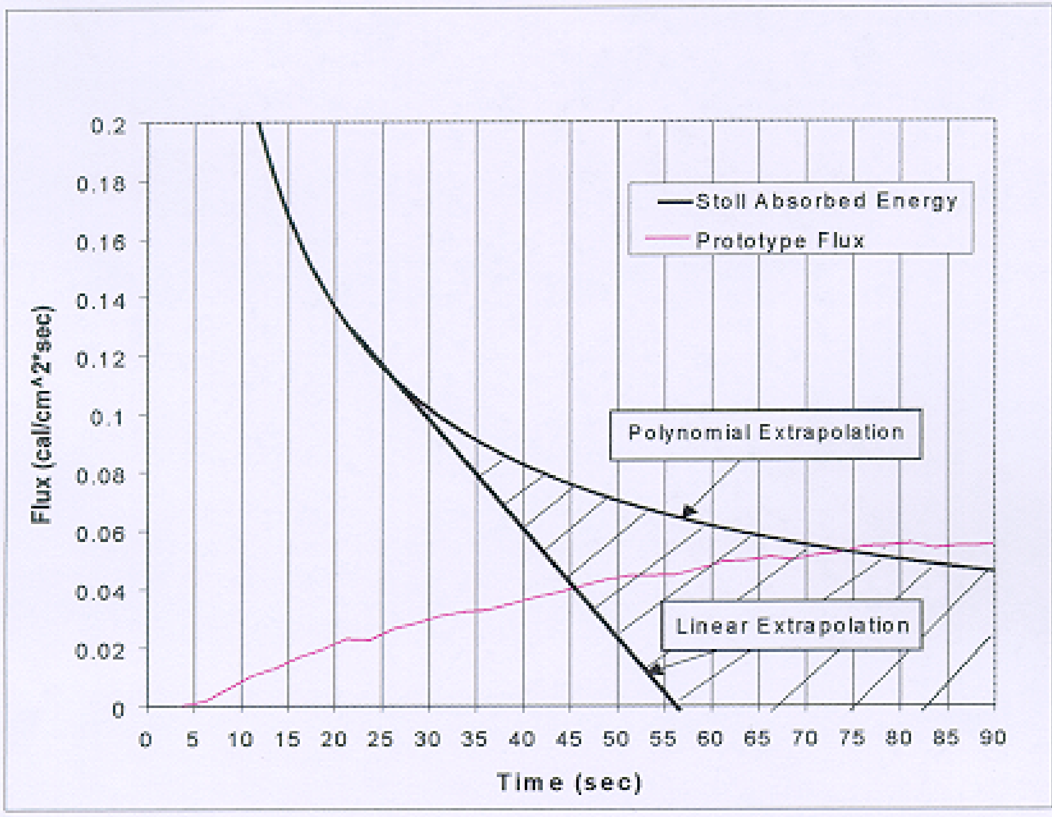


Figure 13. Extended Stoll Criteria Superimposed on NCSU Sensor Response (contact testing configuration).

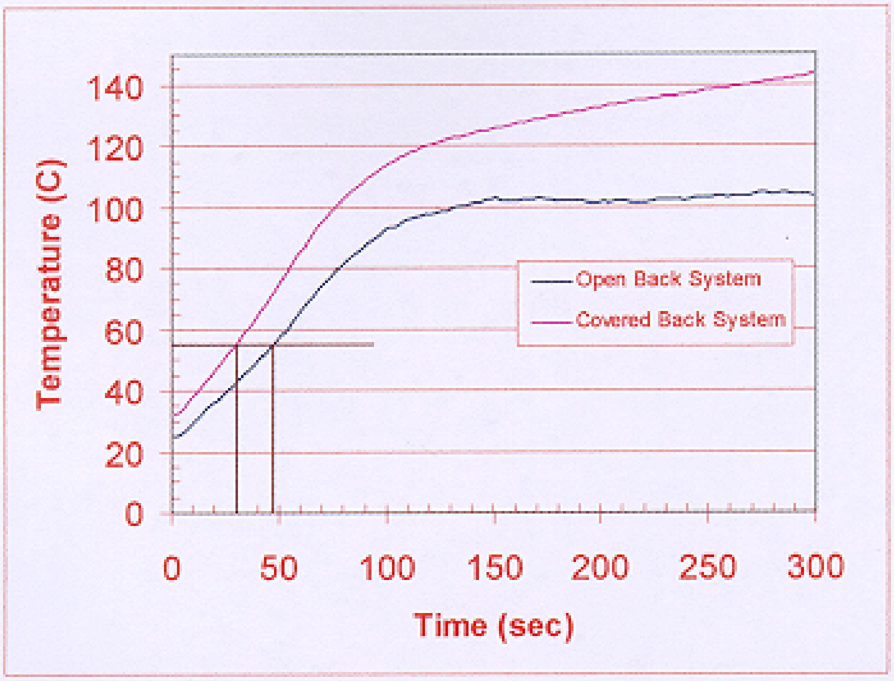


Figure 14. Second Degree Burn Indexed based on 55°C Thermocouple Temperature.

Other analyses were performed to explore applying a burn prediction means to translate heat flux measurements to estimate skin burn injury. Figure 13 shows the Stoll criterion for second degree burn injury superimposed on heat flux measured through the firefighter turnout composite using the prototype sensor (contact testing configuration). In an attempt to estimate the burn protection time beyond the 30 seconds limit of the Stoll criterion, an extended envelope was created by linear and polynomial extrapolations of the data. Consequently, depending on the extrapolation, the limits of the burn protection time estimate vary from 45 seconds (for a linear extrapolation) to 75 seconds (polynomial extrapolation).

Figure 14 provides a comparison of the temperature rise in the thermocouple measuring arrangement for the same turnout composite exposed to the same thermal assault. Using a thermocouple temperature of 55°C to index second degree burn [15], this technique estimates a protection time of 30 seconds for the covered back and 48 seconds for the open back testing configuration.

However, the following caveat must be applied to conclusions requiring interpretation of the heat flux measured by the prototype sensor experiments: These limited tests do not yet provide the basis for definitive comparisons regarding burn predictions made with the NCSU sensor and thermocouple techniques. It should also be emphasized that the forgoing analysis relies on extrapolating the Stoll burn criterion beyond the intended basis for the limits of this model. Additional study of these important issues is clearly needed.

Conclusions

The NCSU water cooled copper sensor is emerging as a reliable and versatile thermal sensor for applications related to evaluating the thermal protective performance of firefighter's protective clothing. Laboratory tests indicate that the sensor provides a consistent and stable reading of heat flux over the wide range thermal exposures of interest in this application. They show that the sensor registers heat flux much like the TPP calorimeter, a device with a long history of use in bench scale testing of thermally protective materials. At the same time, the cooled sensor is capable of extended exposure to thermal flux.

Although the commercial sensors tested perform comparatively well in bare tests, they lack the durability in use that can be expected from the NCSU device. The prototype sensor does not require an inverse heat transfer calculation to estimate heat flux. Direct heat flux measurements are possible.

Future Directions

Preliminary tests indicate that the NCSU water-cooled prototype sensor shows promise as a device for evaluating firefighter protective clothing in prolonged exposures to thermal energy typically encountered near or outside a flashfire environment. Its thermal performance characteristics equals, in several categories, those of commercially available devices, yet it is a rugged instrument. This is significant since sensor durability is a distinctive practical advantage in this testing environment. Comparable evaluation has now provided indications of specific design features that, when incorporated into subsequent versions of the water-cooled sensor, should improve the thermal response. Reduction in the sensor's thermal mass is critically indicated. Other design changes, which could be accomplished in future prototypes would address the following issues:

> The sealants used in the current design are difficult to apply so that variations between sensors are expected due to assembly differences. An improved design will require less sealant and therefore be less prone to sensor-to-sensor fluctuations.
>
> A closed loop coolant system is contemplated to replace the current open loop design. This new system will require design of reservoir, pump and heat exchanger units that are compact and easy to use.
>
> Data acquisition and analysis is currently performed using a desktop PC. A smaller dedicated, handheld unit is contemplated that can be hooked up to several sensors and so serve as a real time monitoring and alarm instrument. This unit will use the algorithms developed by this research, modified for handheld device use.

Finally, more basic research is needed to develop, or adapt, skin burn translation models which are valid for prolonged duration thermal exposure. The availability of such models, coupled with a versatile "Mark II" water-cooled sensor would provide the next generation of firefighter environment research tools.

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Appendix A

Flow Rate Calculations for Sensor Design

Several assumptions were made to provide a preliminary basis for estimating the rate of water flow to the prototype sensor. These assumptions are as follows:

Assumptions:

$T_1 = 21°C = 294.15K$

$P_1 = P_{atm} = 101kPa$

$A_1 = 1.962 \text{ x } 10^{-5}m^2$

$T_2 = 31°C = 304.15K$

$P_2 = P_{atm} = 101kPa$

$A_2 = 1.962 \text{ x } 10^{-5}m^2$

$A_d = Area\ Exposed\ to\ Heat\ Flux = 0.0012m^2$

$\dot{Q} = 2cal / cm^2 * s$

$\rho_{H2O} = 1000kg/m^3$

$C_p = 4.18kJ / kg * K$

Where T_1 is the temperature of the water flowing into the sensor, T_2 is the temperature of the water flowing out of the sensor, P_1 and P_2 are the pressures at the points of entrance and exit of the water. A_1 and A_2 are the areas associated with the area of the fitting for water flow into and out of the sensor. A_d is the area of the copper disk being exposed to the heat source. $\dot{Q}$ is the associated heat flux, ρ_{H2O} is the density and C_p is the specific heat of the water at normal room temperature and pressure.

By converting $\dot{Q}$ to joules and C_p to joules/ gram*Kelvin, we calculated as follows:

$$\dot{Q} = \frac{2cal}{cm^2 * s} * \frac{4.184J}{1cal} * \frac{1cm^2}{10^{-4}m^2} * 0.0021m^2 = 105.05J/s$$

$$C_p = \frac{4.184kJ}{kg * K} * \frac{10^{-3}kg}{1g} * \frac{1J}{10^{-3}kJ} = 4.184J/g * K$$

We stipulate that, at steady state, $\dot{Q}$ is equal to the mass flow rate times the specific heat times the difference in water temperature entering and exiting the sensor, ΔT. The mass flow rate is then calculated as:

$$\dot{Q} = \dot{m} C_p \Delta T$$

$$105.05 J/s = \dot{m}(4.184 J/g*K)(304.15K - 294.015K)$$

$$\dot{m} = {}^{105.05 J/s}\big/_{(4.184 J/g*K)(10K)}$$

$$\dot{m} = 2.51 g/s$$

Proceeding to convert the mass flow rate from grams/second to liters/sec.

$$\dot{m} = \frac{2.51g}{s} * \frac{1m^3}{10^6 g} * \frac{10^3 Liters}{1m^3} = 0.00251 Liters/s$$

Consequently, the velocity of the cooling water is determined as:

$$\dot{m} = \rho * V * A = 10^6 g * V * 1.962 \text{ x } 10^{-5} m^2$$

$$V = \frac{\dot{m}}{\rho * A} = \frac{2.51 g/s}{10^6 g/m^3 * 1.962 \text{ x } 10^{-5} m^2} = 0.12793 m/s$$

Appendix B

Detailed Test Data

The following tables list the test results obtained during the following tests:

Table 1. Sensor Characterization - All Temperatures.

Table 2. Sensor Characterization – Differential Temperature

Table 3. Differential Temperature versus Heat Flux for all Flow Rates

Table 4. Thermocouple Temperature Readings for Open and Covered Back Systems.

Table 5. Sensor Response and Heat Flux for Turnout Composite- Both Mounts

Table 1. Sensor Characterization - All Temperatures.

Exposure 0.15 cal/cm^2*sec at 0.93g/sec Flow Rate, Time vs. Temperature.

TIME (SEC)	WATER IN TEMP (°C)	SENSOR TEMP (°C)	WATER OUT TEMP (°C)
1.20	25.65	26.51	25.95
3.70	25.66	27.21	26.03
6.20	25.66	27.65	26.26
8.70	25.67	27.78	26.39
11.20	25.68	27.95	26.47
13.70	25.64	28.08	26.50
16.20	25.64	28.11	26.52
18.70	25.65	28.11	26.52
21.20	25.65	28.03	26.50
23.70	25.66	27.93	26.55
26.20	25.65	28.08	26.55
28.70	25.67	28.18	26.56
31.20	25.65	28.19	26.58
33.70	25.65	28.17	26.56
36.20	25.66	28.25	26.58
38.70	25.65	28.36	26.59
41.20	25.64	28.38	26.61
43.70	25.65	28.41	26.64
46.21	25.65	28.47	26.64
48.71	25.66	28.44	26.66
51.21	25.66	28.45	26.68
53.71	25.65	28.48	26.67
56.21	25.66	28.51	26.71
58.71	25.65	28.47	26.73
61.21	25.67	28.48	26.73
63.71	25.67	28.52	26.76
66.21	25.67	28.51	26.78
68.71	25.68	28.57	26.78

71.21	25.69	28.63	26.81
73.71	25.69	28.57	26.81
76.21	25.69	28.61	26.79
78.71	25.70	28.65	26.85
81.21	25.70	28.69	26.84
83.71	25.71	28.71	26.83
86.21	25.72	28.76	26.85
88.71	25.71	28.81	26.88
91.21	25.73	28.72	26.86
93.71	25.72	28.73	26.88
96.21	25.73	28.77	26.92
98.71	25.73	28.71	26.96
101.21	25.73	28.64	26.98
103.71	25.74	28.70	27.01
106.21	25.74	28.80	27.02
108.71	25.74	28.82	27.06
111.21	25.74	28.80	27.04
113.71	25.75	28.86	27.05
116.21	25.75	28.88	27.12
118.71	25.75	28.88	27.08
121.21	25.75	28.93	27.10
123.71	25.76	28.92	27.12
126.21	25.77	28.91	27.11
128.71	25.76	28.91	27.12
131.21	25.76	28.88	27.13
133.72	25.77	28.97	27.18
136.22	25.76	28.98	27.22
138.72	25.78	29.01	27.24
141.22	25.77	29.03	27.22
143.72	25.78	29.00	27.22
146.22	25.76	29.01	27.26

148.72	25.77	29.01	27.26
151.22	25.76	29.05	27.22
153.72	25.78	29.13	27.28
156.22	25.77	29.16	27.27
158.72	25.77	29.11	27.26
161.22	25.77	29.15	27.28
163.72	25.77	29.16	27.29
166.22	25.76	29.11	27.32
168.72	25.77	29.08	27.31
171.22	25.77	29.09	27.33
173.72	25.77	29.09	27.33
176.22	25.78	29.10	27.35
178.72	25.78	29.09	27.30
181.22	25.76	29.10	27.32
183.72	25.76	29.13	27.34
186.22	25.76	29.21	27.31
188.72	25.76	29.21	27.33
191.22	25.77	29.18	27.34
193.72	25.77	29.16	27.37
196.22	25.76	29.19	27.38
198.72	25.77	29.17	27.40
201.22	25.76	29.17	27.41
203.72	25.76	29.17	27.41
206.22	25.77	29.24	27.42
208.72	25.78	29.29	27.41
211.22	25.76	29.31	27.41
213.72	25.76	29.28	27.42
216.22	25.76	29.26	27.42
218.72	25.76	29.21	27.45
221.22	25.74	29.25	27.45
223.73	25.75	29.27	27.48

226.23	25.76	29.26	27.51
228.73	25.77	29.23	27.50
231.23	25.77	29.24	27.44
233.73	25.76	29.34	27.50
236.23	25.76	29.31	27.53
238.73	25.77	29.29	27.50
241.23	25.76	29.32	27.51
243.73	25.77	29.40	27.52
246.23	25.76	29.37	27.49
248.73	25.77	29.38	27.53
251.23	25.75	29.40	27.53
253.73	25.76	29.43	27.54
256.23	25.74	29.42	27.53
258.73	25.76	29.41	27.58
261.23	25.77	29.42	27.57
263.73	25.75	29.42	27.57
266.23	25.77	29.36	27.59
268.73	25.77	29.35	27.59
271.23	25.77	29.37	27.59
273.73	25.76	29.39	27.60
276.23	25.78	29.38	27.59
278.73	25.77	29.35	27.57
281.23	25.78	29.34	27.58
283.73	25.76	29.33	27.60
286.23	25.77	29.35	27.61
288.73	25.76	29.38	27.61
291.23	25.75	29.38	27.58
293.73	25.76	29.46	27.59
296.23	25.77	29.44	27.64
298.73	25.75	29.47	27.59

Table 2. Sensor Characterization – Differential Temperature

Exposure 0.15 cal /cm^2*sec at 0.93g/sec Flow Rate, Time vs. Temperature w/ Delta T.

TIME (SEC)	WATER IN TEMP (°C)	SENSOR TEMP (°C)	WATER OUT TEMP (°C)	DELTA T (°C)
1.20	25.65	26.51	25.95	0.56
3.70	25.66	27.21	26.03	1.18
6.20	25.66	27.65	26.26	1.39
8.70	25.67	27.78	26.39	1.39
11.20	25.68	27.95	26.47	1.48
13.70	25.64	28.08	26.50	1.58
16.20	25.64	28.11	26.52	1.59
18.70	25.65	28.11	26.52	1.58
21.20	25.65	28.03	26.50	1.52
23.70	25.66	27.93	26.55	1.38
26.20	25.65	28.08	26.55	1.52
28.70	25.67	28.18	26.56	1.61
31.20	25.65	28.19	26.58	1.62
33.70	25.65	28.17	26.56	1.61
36.20	25.66	28.25	26.58	1.67
38.70	25.65	28.36	26.59	1.76
41.20	25.64	28.38	26.61	1.76
43.70	25.65	28.41	26.64	1.78
46.21	25.65	28.47	26.64	1.83
48.71	25.66	28.44	26.66	1.79
51.21	25.66	28.45	26.68	1.77
53.71	25.65	28.48	26.67	1.81
56.21	25.66	28.51	26.71	1.79
58.71	25.65	28.47	26.73	1.75
61.21	25.67	28.48	26.73	1.75
63.71	25.67	28.52	26.76	1.76
66.21	25.67	28.51	26.78	1.74
68.71	25.68	28.57	26.78	1.80

71.21	25.69	28.63	26.81	1.82
73.71	25.69	28.57	26.81	1.76
76.21	25.69	28.61	26.79	1.82
78.71	25.70	28.65	26.85	1.80
81.21	25.70	28.69	26.84	1.85
83.71	25.71	28.71	26.83	1.88
86.21	25.72	28.76	26.85	1.92
88.71	25.71	28.81	26.88	1.93
91.21	25.73	28.72	26.86	1.85
93.71	25.72	28.73	26.88	1.85
96.21	25.73	28.77	26.92	1.86
98.71	25.73	28.71	26.96	1.75
101.21	25.73	28.64	26.98	1.66
103.71	25.74	28.70	27.01	1.70
106.21	25.74	28.80	27.02	1.78
108.71	25.74	28.82	27.06	1.76
111.21	25.74	28.80	27.04	1.76
113.71	25.75	28.86	27.05	1.81
116.21	25.75	28.88	27.12	1.76
118.71	25.75	28.88	27.08	1.80
121.21	25.75	28.93	27.10	1.83
123.71	25.76	28.92	27.12	1.80
126.21	25.77	28.91	27.11	1.80
128.71	25.76	28.91	27.12	1.79
131.21	25.76	28.88	27.13	1.75
133.72	25.77	28.97	27.18	1.78
136.22	25.76	28.98	27.22	1.76
138.72	25.78	29.01	27.24	1.77
141.22	25.77	29.03	27.22	1.81
143.72	25.78	29.00	27.22	1.78
146.22	25.76	29.01	27.26	1.75

148.72	25.77	29.01	27.26	1.75
151.22	25.76	29.05	27.22	1.83
153.72	25.78	29.13	27.28	1.85
156.22	25.77	29.16	27.27	1.89
158.72	25.77	29.11	27.26	1.86
161.22	25.77	29.15	27.28	1.88
163.72	25.77	29.16	27.29	1.87
166.22	25.76	29.11	27.32	1.79
168.72	25.77	29.08	27.31	1.77
171.22	25.77	29.09	27.33	1.76
173.72	25.77	29.09	27.33	1.76
176.22	25.78	29.10	27.35	1.76
178.72	25.78	29.09	27.30	1.79
181.22	25.76	29.10	27.32	1.78
183.72	25.76	29.13	27.34	1.79
186.22	25.76	29.21	27.31	1.90
188.72	25.76	29.21	27.33	1.89
191.22	25.77	29.18	27.34	1.84
193.72	25.77	29.16	27.37	1.80
196.22	25.76	29.19	27.38	1.82
198.72	25.77	29.17	27.40	1.77
201.22	25.76	29.17	27.41	1.76
203.72	25.76	29.17	27.41	1.77
206.22	25.77	29.24	27.42	1.82
208.72	25.78	29.29	27.41	1.88
211.22	25.76	29.31	27.41	1.90
213.72	25.76	29.28	27.42	1.86
216.22	25.76	29.26	27.42	1.84
218.72	25.76	29.21	27.45	1.76
221.22	25.74	29.25	27.45	1.79
223.73	25.75	29.27	27.48	1.79

226.23	25.76	29.26	27.51	1.76
228.73	25.77	29.23	27.50	1.74
231.23	25.77	29.24	27.44	1.79
233.73	25.76	29.34	27.50	1.84
236.23	25.76	29.31	27.53	1.78
238.73	25.77	29.29	27.50	1.78
241.23	25.76	29.32	27.51	1.81
243.73	25.77	29.40	27.52	1.88
246.23	25.76	29.37	27.49	1.88
248.73	25.77	29.38	27.53	1.85
251.23	25.75	29.40	27.53	1.87
253.73	25.76	29.43	27.54	1.89
256.23	25.74	29.42	27.53	1.89
258.73	25.76	29.41	27.58	1.83
261.23	25.77	29.42	27.57	1.85
263.73	25.75	29.42	27.57	1.85
266.23	25.77	29.36	27.59	1.77
268.73	25.77	29.35	27.59	1.76
271.23	25.77	29.37	27.59	1.78
273.73	25.76	29.39	27.60	1.80
276.23	25.78	29.38	27.59	1.79
278.73	25.77	29.35	27.57	1.78
281.23	25.78	29.34	27.58	1.76
283.73	25.76	29.33	27.60	1.73
286.23	25.77	29.35	27.61	1.75
288.73	25.76	29.38	27.61	1.77
291.23	25.75	29.38	27.58	1.80
293.73	25.76	29.46	27.59	1.87
296.23	25.77	29.44	27.64	1.80
298.73	25.75	29.47	27.59	1.88
			Average Delta T (°C)	1.81

Table 3. Differential Temperature versus Heat Flux for all Flow Rates and all Heat Flux Exposures for Prototype Sensor

EXPOSURE OF 0.15 CAL/CM^2*SEC:	**FLOW RATE OF 0.94 G/SEC**
Average Steady State	**Average of Steady State 90% and Above**
1.81	1.79
90 % of Average of Steady State	
1.63	

EXPOSURE OF 0.23 CAL/CM2*SEC:	**FLOW RATE OF 0.94 G/SEC**
Average Steady State	**Average of Steady State 90% and Above**
2.37	2.28
90 % of Average of Steady State	
2.13	

EXPOSURE OF 1.25 CAL/CM2*SEC:	**FLOW RATE OF 0.94 G/SEC**
Average Steady State	**Average of Steady State 90% and Above**
11.38	11.34
90 % of Average of Steady State	
10.24	

EXPOSURE OF 2.00 CAL/CM2*SEC:	**FLOW RATE OF 0.94 G/SEC**
Average Steady State	**Average of Steady State 90% and Above**
14.80	15.37
90 % of Average of Steady State	
13.32	

Table 3 continued. Differential Temperature versus Heat Flux for all Flow Rates and all Heat Flux Exposures for Prototype Sensor

EXPOSURE OF 0.15 CAL/CM2*SEC:	FLOW RATE OF 1.63 G/SEC
Average Steady State	Average of Steady State 90% and Above
1.67	1.59
90 % of Average of Steady State	
1.50	

EXPOSURE OF 0.23 CAL/CM2*SEC:	FLOW RATE OF 1.63 G/SEC
Average Steady State	Average of Steady State 90% and Above
2.38	2.32
90 % of Average of Steady State	
2.14	

EXPOSURE OF 1.25 CAL/CM2*SEC:	FLOW RATE OF 1.63 G/SEC
Average Steady State	Average of Steady State 90% and Above
11.09	10.75
90 % OF AVERAGE OF STEADY STATE	
9.98	

EXPOSURE OF 2.00 CAL/CM2*SEC:	FLOW RATE OF 1.63 G/SEC
Average Steady State	Average of Steady State 90% and Above
16.05	15.88
90 % of Average of Steady State	
14.44	

Table 3 continued. Differential Temperature versus Heat Flux for all Flow Rates and all Heat Flux Exposures for Prototype Sensor

EXPOSURE OF 0.15 CAL/CM2*SEC:	FLOW RATE OF 2.33 G/SEC
Average Steady State	**Average of Steady State 90% and Above**
1.19	1.17
90 % of Average of Steady State	
1.07	

EXPOSURE OF 0.23 CAL/CM2*SEC:	FLOW RATE OF 2.33 G/SEC
Average Steady State	**Average of Steady State 90% and Above**
2.00	1.93
90 % of Average of Steady State	
1.80	

EXPOSURE OF 1.25 CAL/CM2*SEC:	FLOW RATE OF 2.33 G/SEC
Average Steady State	**Average of Steady State 90% and Above**
11.19	10.85
90 % OF AVERAGE OF STEADY STATE	
10.07	

EXPOSURE OF 2.00 CAL/CM2*SEC:	FLOW RATE OF 2.33 G/SEC
Average Steady State	**Average of Steady State 90% and Above**
14.71	14.51
90 % of Average of Steady State	
13.24	

Table 4. Thermocouple Temperature Readings for Open and Covered Back Systems at 0.23 cal/cm^2*sec

TIME (SEC)	OPEN BACK TC TEMP (°C)		TIME (SEC)	COVERED BACK TC TEMP (°C)
1.20	25.17		1.20	31.81
3.70	25.60		3.70	32.91
6.20	26.63		6.20	34.46
8.70	28.32		8.70	36.61
11.20	30.19		11.20	38.93
13.70	32.23		13.70	41.18
16.20	34.11		16.20	43.30
18.70	35.50		18.70	45.40
21.20	37.07		21.20	47.47
23.70	38.59		23.70	49.57
26.20	40.10		26.20	51.74
28.70	41.85		28.70	53.94
31.20	43.78		31.20	56.21
33.70	45.56		33.70	58.50
36.20	46.99		36.20	60.83
38.70	48.82		38.70	63.20
41.20	50.55		41.20	65.65
43.70	52.54		43.70	68.16
46.20	54.52		46.20	70.75
48.70	56.16		48.70	73.35
51.20	57.92		51.20	76.03
53.70	59.94		53.70	78.74
56.20	62.29		56.20	81.43
58.70	64.66		58.70	84.09
61.20	67.07		61.20	86.68
63.70	69.22		63.70	89.22
66.20	71.03		66.20	91.58
68.70	73.04		68.70	93.92

71.20	75.08		71.20	96.08
73.70	76.88		73.70	98.13
76.20	78.80		76.20	99.99
78.70	80.72		78.70	101.77
81.21	82.31		81.20	103.45
83.70	83.61		83.71	105.05
86.21	85.24		86.21	106.58
88.71	86.66		88.71	108.02
91.21	88.07		91.21	109.38
93.71	89.33		93.71	110.70
96.21	90.76		96.21	111.95
98.71	92.33		98.71	113.15
101.21	93.27		101.21	114.28
103.71	93.58		103.71	115.30
106.21	94.71		106.21	116.25
108.71	95.72		108.71	117.12
111.21	96.32		111.21	117.91
113.71	96.86		113.71	118.64
116.21	97.19		116.21	119.31
118.71	97.57		118.71	119.90
121.21	97.67		121.21	120.46
123.71	98.30		123.71	120.99
126.21	98.72		126.21	121.51
128.71	98.94		128.71	122.04
131.21	99.64		131.21	122.54
133.71	100.13		133.71	123.02
136.21	100.26		136.21	123.45
138.71	100.85		138.71	123.89
141.21	101.39		141.21	124.27
143.71	101.67		143.71	124.65
146.21	102.31		146.21	125.04

148.71	102.61		148.71	125.43
151.21	102.97		151.21	125.81
153.71	102.10		153.71	126.24
156.21	101.93		156.21	126.65
158.71	101.81		158.71	127.08
161.21	101.94		161.21	127.48
163.71	102.26		163.71	127.84
166.22	102.27		166.21	128.19
168.71	102.69		168.71	128.55
171.22	102.89		171.21	128.89
173.71	102.27		173.72	129.23
176.22	102.25		176.22	129.56
178.72	101.97		178.72	129.87
181.22	101.74		181.22	130.23
183.72	101.91		183.72	130.55
186.22	101.87		186.22	130.91
188.72	101.87		188.72	131.25
191.22	101.86		191.22	131.57
193.72	101.65		193.72	131.89
196.22	101.63		196.22	132.24
198.72	101.58		198.72	132.58
201.22	101.72		201.22	132.87
203.72	101.68		203.72	133.21
206.22	101.71		206.22	133.58
208.72	101.95		208.72	133.88
211.22	102.16		211.22	134.21
213.72	101.68		213.72	134.51
216.22	101.59		216.22	134.80
218.72	101.29		218.72	135.03
221.22	101.51		221.22	135.32
223.72	101.99		223.72	135.55

226.22	102.53		226.22	135.76
228.72	102.52		228.72	135.99
231.22	102.71		231.22	136.18
233.72	102.75		233.72	136.32
236.22	102.74		236.22	136.57
238.72	101.96		238.72	136.80
241.22	102.42		241.22	137.06
243.72	102.89		243.72	137.40
246.22	102.97		246.22	137.69
248.72	102.93		248.72	138.03
251.23	103.11		251.22	138.32
253.72	103.38		253.72	138.60
256.23	103.71		256.22	138.84
258.72	103.26		258.72	139.02
261.23	103.61		261.23	139.23
263.73	103.55		263.73	139.47
266.23	103.46		266.23	139.64
268.73	103.36		268.73	139.94
271.23	104.10		271.23	140.20
273.73	104.45		273.73	140.50
276.23	104.44		276.23	140.80
278.73	104.03		278.73	141.05
281.23	104.30		281.23	141.38
283.73	104.38		283.73	141.61
286.23	104.41		286.23	141.83
288.73	104.32		288.73	142.07
291.23	104.14		291.23	142.35
293.73	104.20		293.73	142.68
296.23	103.96		296.23	143.07
298.73	103.77		298.73	143.37

Table 5. Prototype Sensor Response of Heat Flux for Turnout Composite- Both Mounts, Flush Mount and Spaced Mount Data at 0.23 cal/cm^2*sec

TIME (SEC)	DELTA T (°C)	FLUSH MOUNT PREDICTED FLUX		TIME (SEC)	DELTA T (°C)	SPACED PREDICTED FLUX
1.19	0.00	0.00		1.19	0.00	0.00
3.69	0.00	0.00		3.69	0.00	0.00
6.20	0.02	0.00		6.19	0.01	0.00
8.70	0.08	0.01		8.69	0.04	0.00
11.20	0.14	0.01		11.19	0.04	0.00
13.70	0.17	0.01		13.69	0.08	0.01
16.20	0.23	0.02		16.19	0.07	0.01
18.70	0.26	0.02		18.70	0.07	0.01
21.20	0.31	0.02		21.20	0.06	0.00
23.70	0.30	0.02		23.70	0.08	0.01
26.20	0.36	0.03		26.20	0.10	0.01
28.70	0.38	0.03		28.70	0.12	0.01
31.20	0.41	0.03		31.20	0.13	0.01
33.70	0.43	0.03		33.70	0.18	0.01
36.20	0.44	0.03		36.20	0.22	0.02
38.70	0.47	0.03		38.70	0.22	0.02
41.20	0.50	0.04		41.20	0.25	0.02
43.70	0.52	0.04		43.70	0.29	0.02
46.20	0.55	0.04		46.20	0.33	0.02
48.70	0.58	0.04		48.70	0.34	0.03
51.20	0.60	0.04		51.20	0.37	0.03
53.70	0.60	0.04		53.70	0.40	0.03
56.20	0.61	0.04		56.20	0.41	0.03
58.70	0.63	0.05		58.70	0.41	0.03
61.20	0.66	0.05		61.20	0.40	0.03
63.70	0.67	0.05		63.70	0.42	0.03
66.20	0.69	0.05		66.20	0.42	0.03
68.70	0.67	0.05		68.70	0.43	0.03

71.20	0.69	0.05		71.20	0.45	0.03
73.70	0.71	0.05		73.70	0.45	0.03
76.20	0.74	0.05		76.20	0.44	0.03
78.70	0.74	0.05		78.70	0.46	0.03
81.20	0.75	0.06		81.20	0.46	0.03
83.70	0.73	0.05		83.70	0.46	0.03
86.20	0.74	0.05		86.20	0.46	0.03
88.70	0.74	0.05		88.70	0.45	0.03
91.20	0.75	0.06		91.20	0.45	0.03
93.71	0.74	0.05		93.70	0.47	0.03
96.21	0.74	0.05		96.20	0.46	0.03
98.71	0.74	0.05		98.70	0.47	0.04
101.21	0.72	0.05		101.20	0.48	0.04
103.71	0.70	0.05		103.70	0.46	0.03
106.21	0.72	0.05		106.20	0.49	0.04
108.71	0.71	0.05		108.71	0.49	0.04
111.21	0.70	0.05		111.21	0.50	0.04
113.71	0.69	0.05		113.71	0.48	0.04
116.21	0.66	0.05		116.21	0.50	0.04
118.71	0.67	0.05		118.71	0.50	0.04
121.21	0.65	0.05		121.21	0.49	0.04
123.71	0.66	0.05		123.71	0.48	0.04
126.21	0.65	0.05		126.21	0.48	0.04
128.71	0.65	0.05		128.71	0.50	0.04
131.21	0.61	0.05		131.21	0.48	0.04
133.71	0.64	0.05		133.71	0.50	0.04
136.21	0.61	0.05		136.21	0.46	0.03
138.71	0.65	0.05		138.71	0.47	0.03
141.21	0.63	0.05		141.21	0.48	0.04
143.71	0.64	0.05		143.71	0.46	0.03
146.21	0.63	0.05		146.21	0.46	0.03

148.71	0.63	0.05		148.71	0.48	0.04
151.21	0.62	0.05		151.21	0.46	0.03
153.71	0.62	0.05		153.71	0.47	0.03
156.21	0.62	0.05		156.21	0.47	0.03
158.71	0.64	0.05		158.71	0.48	0.04
161.21	0.67	0.05		161.21	0.47	0.03
163.71	0.66	0.05		163.71	0.47	0.04
166.21	0.64	0.05		166.21	0.47	0.03
168.71	0.64	0.05		168.71	0.48	0.04
171.21	0.62	0.05		171.21	0.51	0.04
173.71	0.60	0.04		173.71	0.48	0.04
176.21	0.62	0.05		176.21	0.47	0.03
178.71	0.63	0.05		178.71	0.48	0.04
181.22	0.62	0.05		181.21	0.50	0.04
183.72	0.61	0.05		183.71	0.49	0.04
186.22	0.64	0.05		186.21	0.48	0.04
188.72	0.63	0.05		188.71	0.51	0.04
191.22	0.64	0.05		191.22	0.50	0.04
193.72	0.62	0.05		193.72	0.50	0.04
196.22	0.62	0.05		196.22	0.48	0.04
198.72	0.64	0.05		198.72	0.47	0.04
201.22	0.65	0.05		201.22	0.48	0.04
203.72	0.64	0.05		203.72	0.50	0.04
206.22	0.65	0.05		206.22	0.49	0.04
208.72	0.65	0.05		208.72	0.51	0.04
211.22	0.63	0.05		211.22	0.51	0.04
213.72	0.64	0.05		213.72	0.48	0.04
216.22	0.63	0.05		216.22	0.47	0.04
218.72	0.64	0.05		218.72	0.50	0.04
221.22	0.64	0.05		221.22	0.48	0.04
223.72	0.62	0.05		223.72	0.47	0.04

226.22	0.65	0.05		226.22	0.48	0.04
228.72	0.61	0.05		228.72	0.47	0.03
231.22	0.62	0.05		231.22	0.47	0.03
233.72	0.63	0.05		233.72	0.48	0.04
236.22	0.62	0.05		236.22	0.48	0.04
238.72	0.61	0.05		238.72	0.50	0.04
241.22	0.62	0.05		241.22	0.49	0.04
243.72	0.63	0.05		243.72	0.50	0.04
246.22	0.64	0.05		246.22	0.50	0.04
248.72	0.63	0.05		248.72	0.50	0.04
251.22	0.64	0.05		251.22	0.50	0.04
253.72	0.66	0.05		253.72	0.48	0.04
256.22	0.65	0.05		256.22	0.49	0.04
258.72	0.65	0.05		258.72	0.50	0.04
261.22	0.67	0.05		261.22	0.49	0.04
263.72	0.69	0.05		263.72	0.46	0.03
266.23	0.70	0.05		266.22	0.49	0.04
268.73	0.72	0.05		268.72	0.47	0.03
271.23	0.70	0.05		271.22	0.46	0.03
273.73	0.67	0.05		273.72	0.49	0.04
276.23	0.65	0.05		276.22	0.48	0.04
278.73	0.66	0.05		278.72	0.46	0.03
281.23	0.67	0.05		281.22	0.47	0.04
283.73	0.68	0.05		283.73	0.47	0.03
286.23	0.68	0.05		286.23	0.46	0.03
288.73	0.68	0.05		288.73	0.46	0.03
291.23	0.69	0.05		291.23	0.46	0.03
293.73	0.75	0.06		293.73	0.45	0.03
296.23	0.74	0.05		296.23	0.48	0.04
298.73	0.74	0.06		298.73	0.44	0.03

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The Center for Research on Textile Protection and Comfort (T-PACC) at North Carolina State University conducted a project which had, as its primary objective, the selection and evaluation of sensors that can be used to measure heat transferred through firefighter protective clothing materials, with the ultimate goal of applying this knowledge base to the development of rugged, and dependable laboratory benchtop and fire scene specific sensor technology. The purpose of this final report is to summarize the findings of this project and to recommend future directions in protection measuring heat flux sensor development.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

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